

# Using Single Photons for WIMP Searches at the ILC

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We consider analysis targets at the International Linear Collider in which only a single photon can be observed. For such processes, we have developed a method which uses likelihood distributions using the full event information (photon energy and angle). The method was applied to a search for neutralino pair production with a photon from initial state radiation (ISR) in the case of supergravity in which the neutralino is the lightest supersymmetric particle. We determine the cross section required to observe the neutralino pair production with ISR as a function of the neutralino mass in the range of 100 to 250 GeV.

## 1 Introduction

Weakly interacting massive particles (WIMPs) are important study targets in current and future collider experiments since the WIMPs provide a solution to the dark matter problem. In this study, we investigate the prospects of discovering the direct pair production of WIMPs at the International Linear Collider (ILC) using the energy and angle spectra of the photons from initial state radiation (ISR) [1]. We make the assumption that, among the particles beyond the Standard Model, the WIMPs are the only kinematically accessible at the center-of-mass (CM) energy of 500 GeV proposed for the ILC. Similar past searches using single photons have been performed by e.g. [2, 3].

Prospects of such measurements have been discussed in many literature [4, 5, 6, 7] and, in particular, at the ILC [8] which uses a cut-and-count approach. Our method uses the two-dimensional energy and angle distributions of the ISR photon and thus exploits the full information of the event. We apply this method to an example case of minimal supergravity (mSUGRA) [9, 10, 11] in which the neutralino is the lightest supersymmetric particle (LSP). The mSUGRA parameters have been chosen so that the LSP becomes bino-like; under this assumption, the dominant contribution to the neutralino pair production becomes the  $t$ -channel diagram shown in Figure 1. We perform a likelihood analysis based on the photon distributions and derive cross-section limits. We assume an integrated luminosity of  $500 \text{ fb}^{-1}$  at  $\sqrt{s} = 500 \text{ GeV}$ .

## 2 Signal and background samples

Signal events have been generated using WHIZARD [12]. A GEANT4-based [13] simulation of the detector response was carried out by Mokka [14] using the International Large Detector (ILD) Concept [15]. For the background studies, we used the full Standard Model samples which were generated for the ILD Letter of Intent [15].

Signal samples were generated with two different LSP masses by varying the mSUGRA parameter  $M_{1/2}$ , resulting in LSP masses of approximately 150 and 200 GeV. The other

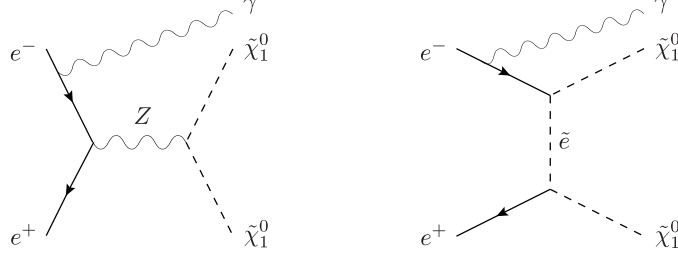


Figure 1: Tree-level diagrams for neutralino pair production with initial state radiation:  $s$ -channel (left) and  $t$ -channel (right).

mSUGRA parameters have been fixed to the following values:  $m_0 = 300$  GeV,  $A_0 = 0$ ,  $\tan \beta = 5$  and  $\text{sgn}(\mu) = +1$ . The mass spectra have been computed using SOFTSUSY [16]; the relevant values are summarized in Table 1. The default cuts of WHIZARD have been

	Sample A	Sample B
$m_{\tilde{\chi}_1^0}$ (LSP)	151 GeV	205 GeV
$m_{\tilde{e}_L}$	395 GeV	453 GeV
$m_{\tilde{e}_R}$	333 GeV	354 GeV
$M_{1/2}$	375 GeV	500 GeV

Table 1: Mass spectra of signal samples.

modified to allow the generation of photons with energy greater than 0.1 GeV and  $|\cos \theta| < 0.995$  where the angle  $\theta$  is taken to be between the direction of the photon momentum and the beam axis. The signal samples have been generated separately for different polarizations for the electron and positron beams. For the case of  $m_{\tilde{\chi}_1^0} = 150$  GeV, the cross sections restricted to the energy and angle ranges used for the event generation are  $\sigma(e_R^- e_L^+ \rightarrow \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 56$  fb and  $\sigma(e_L^- e_R^+ \rightarrow \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 1.9$  fb; for the case of 200 GeV, the respective cross sections are 18 fb and 0.55 fb. The difference in the cross section between the two polarization combinations arises primarily due to the weak hypercharge of the chiral fields and, to a lesser extent, the difference in the scalar electron masses. The two samples were mixed with appropriate weights to yield a sample with the beam polarizations  $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$ .

We list the dominant background processes after the event selection in Table 2.

Process	Cross section
$\gamma\gamma \rightarrow \ell^+ \ell^-$	$1.1 \times 10^3$ fb
$e^+ e^- \rightarrow \gamma \nu_\ell \bar{\nu}_\ell$	$7.8 \times 10^2$ fb

Table 2: Dominant background processes: the cross sections in the table are calculated after the event selection as described in Section 3. The lepton generations ( $\ell = e, \mu, \tau$ ) are summed in the cross section numbers.

### 3 Event reconstruction

We rely on the Pandora Particle Flow Algorithm [17] for the reconstruction of calorimeter clusters and charged particles. A single highly energetic photon often results into multiple clusters. In order to recover the split clusters, we merge the clusters which lie within a cone of an opening angle of 1.5 degree around the most energetic cluster. For the event selection, we require that there are no charged particles in the event. In addition, we require that there are no other clusters aside from the merged cluster. The merged cluster is required to have an energy greater than 0.5 GeV. For the particle identification, we take the energy deposits in the electromagnetic calorimeter  $E_{\text{ECAL}}$  and the hadronic calorimeter  $E_{\text{HCAL}}$  to compute the energy fraction  $E_{\text{ECAL}}/(E_{\text{ECAL}} + E_{\text{HCAL}})$  which is required to be greater than 0.9. The reconstruction efficiency of signal events as a function of energy and angle is shown in Figure 2. The overall signal efficiency is 94% after the event selection.

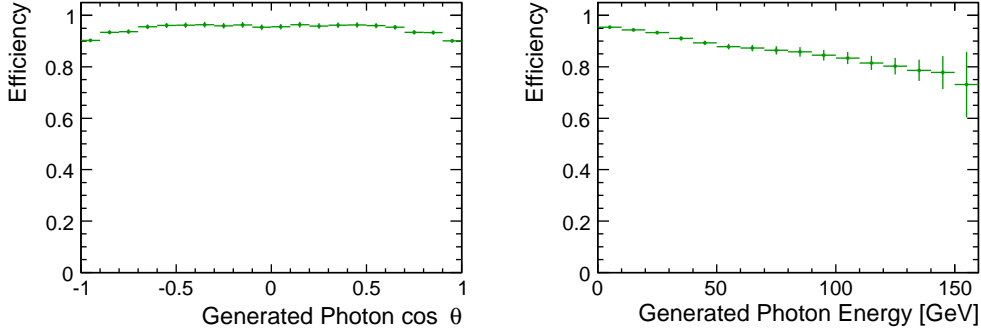


Figure 2: Reconstruction efficiency as a function of angle and energy after the photon cluster merging.

### 4 Likelihood analysis

We perform a binned likelihood analysis using the two dimensional distribution of the photon energy (logarithmic scale) and angle. We choose a binning such that the number of bins is  $N = 96$ , with the binning widths shown in Figure 3. The choice of  $\log E$  instead of  $E$  is motivated by the fact that the ISR photon distribution diverges at low energy. The angle is folded around  $\theta = \pi/2$ , to exploit the symmetry of the distribution. The bin size is adjusted to ensure the presence of sufficient signal events in each bin. The log likelihood ratio is defined as follows:

$$\ln \mathcal{L}(n_1, n_2, \dots, n_N) = \sum_{i=1}^N \ln \frac{P(n_i; b_i + s_i)}{P(n_i; b_i)} \quad (1)$$

where  $n_i$  is the observed number of events in the  $i$ -th bin,  $b_i$  is the expected number of background events in the  $i$ -th bin,  $s_i$  is the expected number of signal events in the  $i$ -th bin, and  $P(n; \lambda) = \lambda^n e^{-\lambda} / n!$  is the Poisson probability density function with the expectation value of  $\lambda$ . The  $m_{\tilde{\chi}_1^0} = 150$  GeV sample was used to build the template signal shape; the same signal shape was used to build likelihood functions even for different masses in the

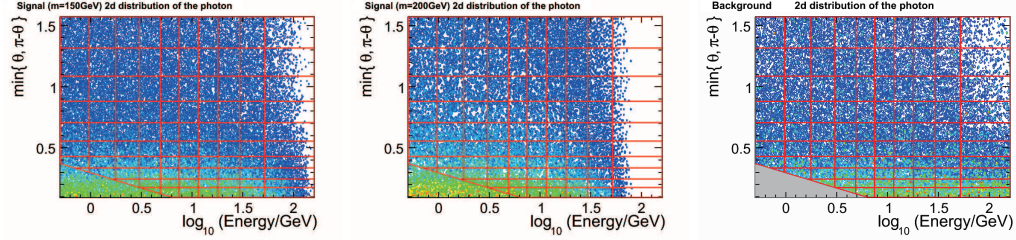


Figure 3: Two-dimensional distributions for signal events with  $m_{\tilde{\chi}_1^0} = 150$  GeV (left),  $m_{\tilde{\chi}_1^0} = 200$  GeV (center), and background events (right). The horizontal axis is the photon energy in logarithmic scale. The vertical axis is the photon angle in radians, folded around  $\pi/2$ . The binning is shown as red lines; the lower-left corner is cut off to make the binning consistent with the cuts in the background sample.

subsequent analysis, since the true mass is not known *a priori*. The likelihood distributions are obtained by performing Monte-Carlo test experiments whereby the observed number of events in each bin is fluctuated using Poissonian random numbers. The resulting likelihood distributions for background plus signal events ( $\lambda_i = b_i + s_i$ ) are compared with that for background events only ( $\lambda_i = b_i$ ) to compute the probability for observing the WIMP signal, as shown in Figure 4. From this distribution, we calculate the expected significance

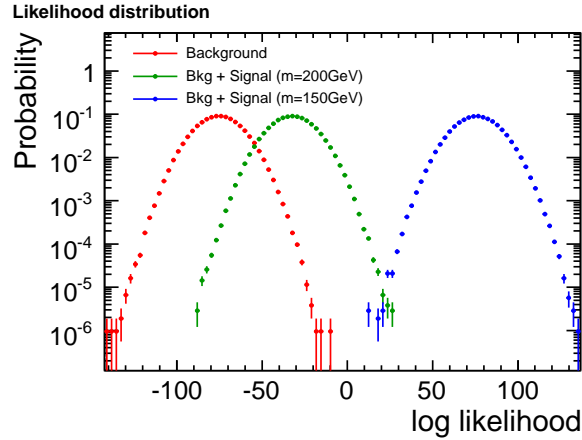


Figure 4: Distribution of log-likelihood values for background only (red), background and signal with  $m_{\tilde{\chi}_1^0} = 200$  GeV (green), and background and signal with  $m_{\tilde{\chi}_1^0} = 150$  GeV (blue). The vertical axis is the probability density for a given log-likelihood value.

for each neutralino mass. We estimate the significance by computing the probability that the backgrounds fluctuate to deviate more than the median of the signal likelihood. In the case of  $m_{\tilde{\chi}_1^0} = 200$  GeV, the estimated significance is  $3.1\sigma$ ; in the case of  $m_{\tilde{\chi}_1^0} = 150$  GeV, the estimated significance is well above  $5\sigma$ . The difference in the significance between the two cases is mostly due to the difference in the cross section.

In the case of a more general WIMP scenario, the dependence of the signal cross section on the WIMP mass is expected to be considerably different. In order to take this effect into account, we performed a scan of likelihood values by varying the WIMP mass and the cross section independently. The best signal separation power can be attained when the correct signal template function is used; assuming this is the case, we keep our mSUGRA signal template. Additional signal samples were generated using 15 different WIMP mass points ranging from 100 GeV to 240 GeV by varying  $M_{1/2}$ . For this study, we use the beam polarizations of  $(P_{e-}, P_{e+}) = (+1.0, -1.0)$ . We obtain the cross section limit, defined as the cross section which gives a 50% probability of  $5\sigma$  observation, as a function of the WIMP mass.

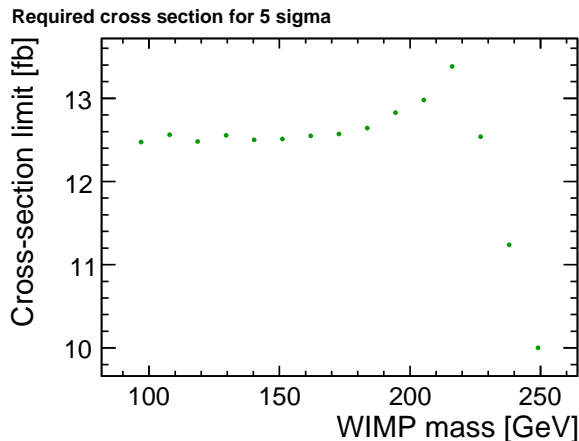


Figure 5: Cross section limits for WIMP observation. The vertical axis is the cross-section limit of the polarization combination  $(P_{e-}, P_{e+}) = (+1.0, -1.0)$  integrated over the kinematically allowed region in this analysis.

For a given mass, we adjusted the cross section until it yielded the desired probability of observing the signal. We performed  $10^6$  Monte-Carlo test experiments at each step of testing the cross section. A binary search was used to find the cross section limit efficiently. The cross section limit as a function of the WIMP mass is plotted in Figure 5. If the cross section is at least 14 fb, the WIMP can be observed. Around the mass of 200 GeV, the required cross section increases since the likelihood function is constructed using the template signal shape for  $m_{\tilde{\chi}_1^0} = 150$  GeV. As the WIMP mass approaches 250 GeV, the required cross section becomes smaller since the photon energy distribution peaks at the low energy region, thereby allowing it to be discriminated against the background shape. Note, however, that if one fixes the model and let the mass approach 250 GeV, the cross section decreases faster than the cross-section limit. Thus, this result is consistent with the fact that the heavier neutralino is more difficult to observe.

## 5 Conclusions

We have looked at the mSUGRA neutralino search as an example of a WIMP search with single photons using the two-dimensional distribution of the ISR photon energy and the

angle. We compared the likelihood distributions and calculated the probability to achieve  $5\sigma$  observation. In our mSUGRA model, the  $m_{\tilde{\chi}_1^0} = 150$  GeV case can be easily observed, while the  $m_{\tilde{\chi}_1^0} = 200$  GeV case has the significance of  $3.1\sigma$ . We obtained cross-section limits as a function of the neutralino mass. WIMPs created through the  $t$ -channel with the cross section of over 15 fb can be observed with the  $5\sigma$  significance at the ILC with  $\sqrt{s} = 500$  GeV. In principle, this method can be applied to a broader class of WIMP searches with ISR photons.

## Acknowledgments

The authors would like to thank all members of the ILC physics subgroup [18] for useful discussions. This study is supported in part by the Creative Scientific Research Grant No. 18GS0202 of the Japan Society for Promotion of Science.

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